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Title: Basics of Gamma Ray Detection

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# Basics of Gamma Ray Detection

## Fundamentals of Non-Destructive Assay for International Safeguards

Los Alamos National Laboratory

September 25, 2017

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*Los Alamos National Laboratory*



**SAFEGUARD** NUCLEAR MATERIALS TO  
PREVENT THEIR DIVERSION OR THEFT



**CONTROL** THE SPREAD OF WMD-RELATED  
MATERIAL, EQUIPMENT AND TECHNOLOGY



NEGOTIATE, MONITOR AND **VERIFY**  
COMPLIANCE WITH INTERNATIONAL  
NONPROLIFERATION AND ARMS CONTROL  
TREATIES AND AGREEMENTS



**DEVELOP** PROGRAMS AND STRATEGIES TO  
ADDRESS EMERGING NONPROLIFERATION  
AND ARMS CONTROL THREATS AND  
CHALLENGES



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## Terminal Learning Objective

- Explain the origin of x-rays and gamma rays, gamma ray interactions with matter, detectors and electronics used in gamma ray-spectrometry, and features of a gamma-ray spectrum for nuclear material that is safeguarded.



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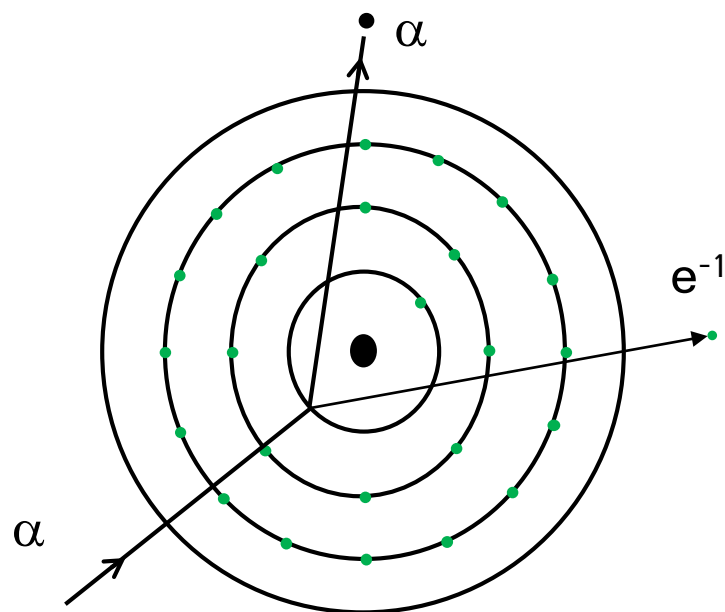
## Enabling Learning Objectives

- Describe the origin of x-rays and gamma-rays, the radioactive decay characteristics for uranium and plutonium and resulting photon emission yields.
- Explain how gamma-rays interact with matter: photoelectric effect, Compton scatter, pair production and annihilation, attenuation.
- List features specific to a uranium and plutonium gamma-ray spectrum
- Describe detector parameters: resolution, efficiency, dead-time
- Recognize detector technologies: scintillators and semiconductors.
- Explain how gammas interact with a detector to create a spectrum, and the electronic settings that may be adjusted in the course of calibration: energy, pole-zero, integration time.
- Understand gamma-ray spectrometry statistical concepts for precision and bias.



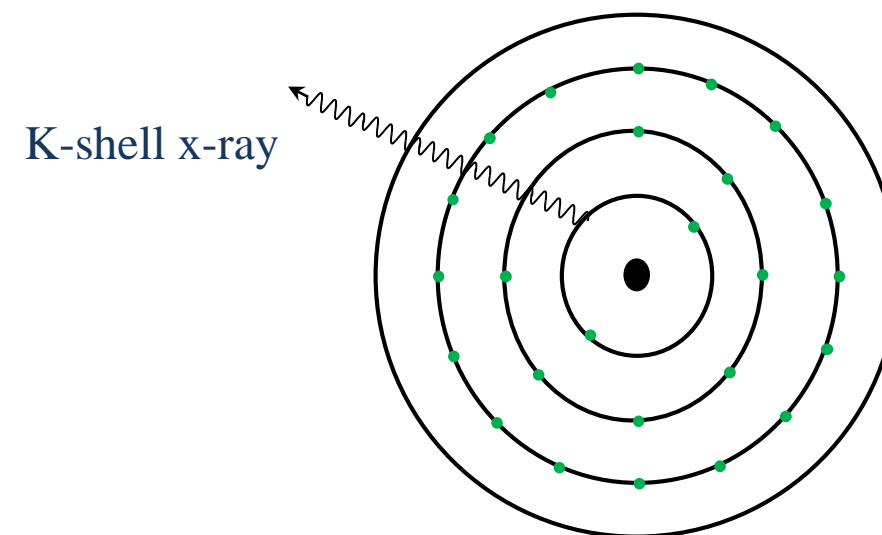
# Origin of X-rays

## Making an X-Ray Transition Possible



PARTICLE KNOCKS OUT AN  
ATOMIC ELECTRON AND  
LEAVES A VACANCY

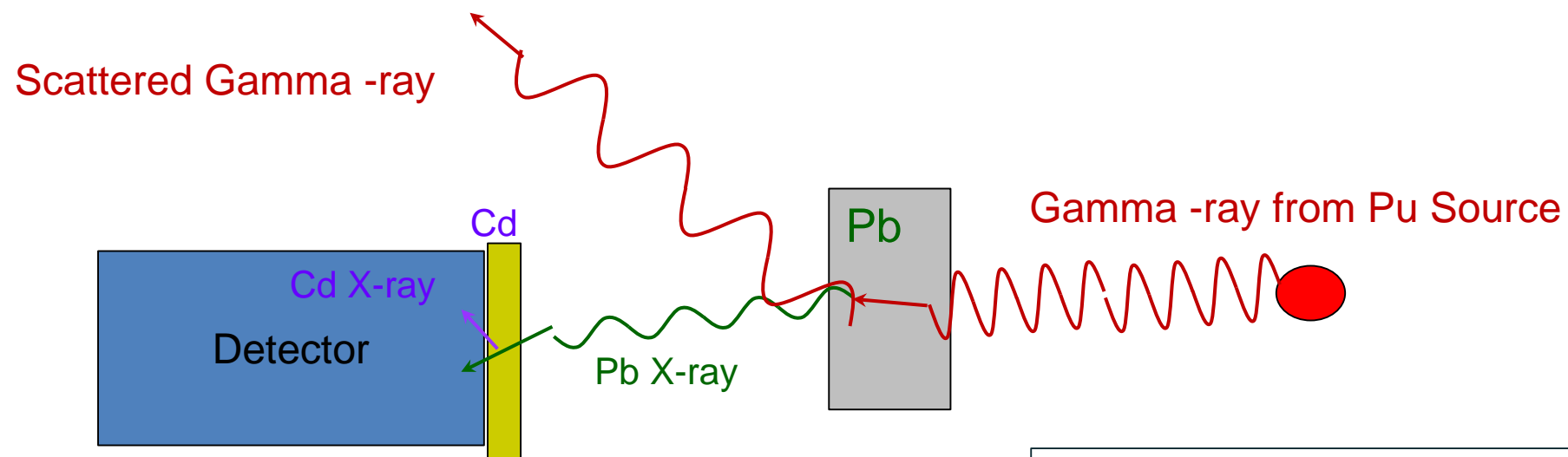
## Producing the X Ray



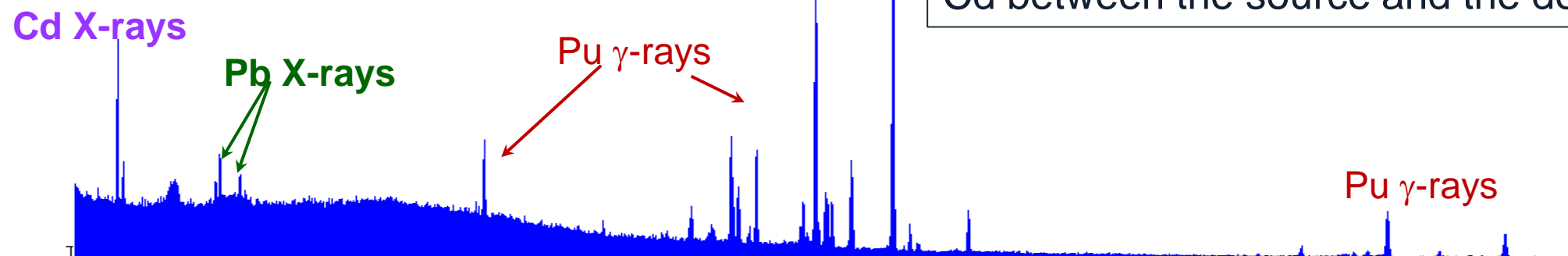
AN OUTER ELECTRON “FALLS”  
INTO THE “HOLE”, AND GIVES UP  
ENERGY IN THE FORM OF AN X-  
RAY



# X-Ray Fluorescence Example



Spectrum of Plutonium Item with Pb and Cd between the source and the detector





## Example X-ray Energies

Element	Energy [keV]	Level	Usage
Cd	23.174	$K_{\alpha 1}$	Low-E gamma filter, thermal neutron absorber
	26.095	$K_{\beta 1}$	
Pb	74.969	$K_{\alpha 1}$	Generic gamma-ray shielding material
	84.938	$K_{\beta 1}$	
W	59.318	$K_{\alpha 1}$	Detector collimators, gamma-ray shielding
	67.244	$K_{\beta 1}$	
U	98.434	$K_{\alpha 1}$	Material itself, plus DU is a common gamma shield
	111.298	$K_{\beta 1}$	
Pu	103.734	$K_{\alpha 1}$	Material itself
	117.228	$K_{\beta 1}$	

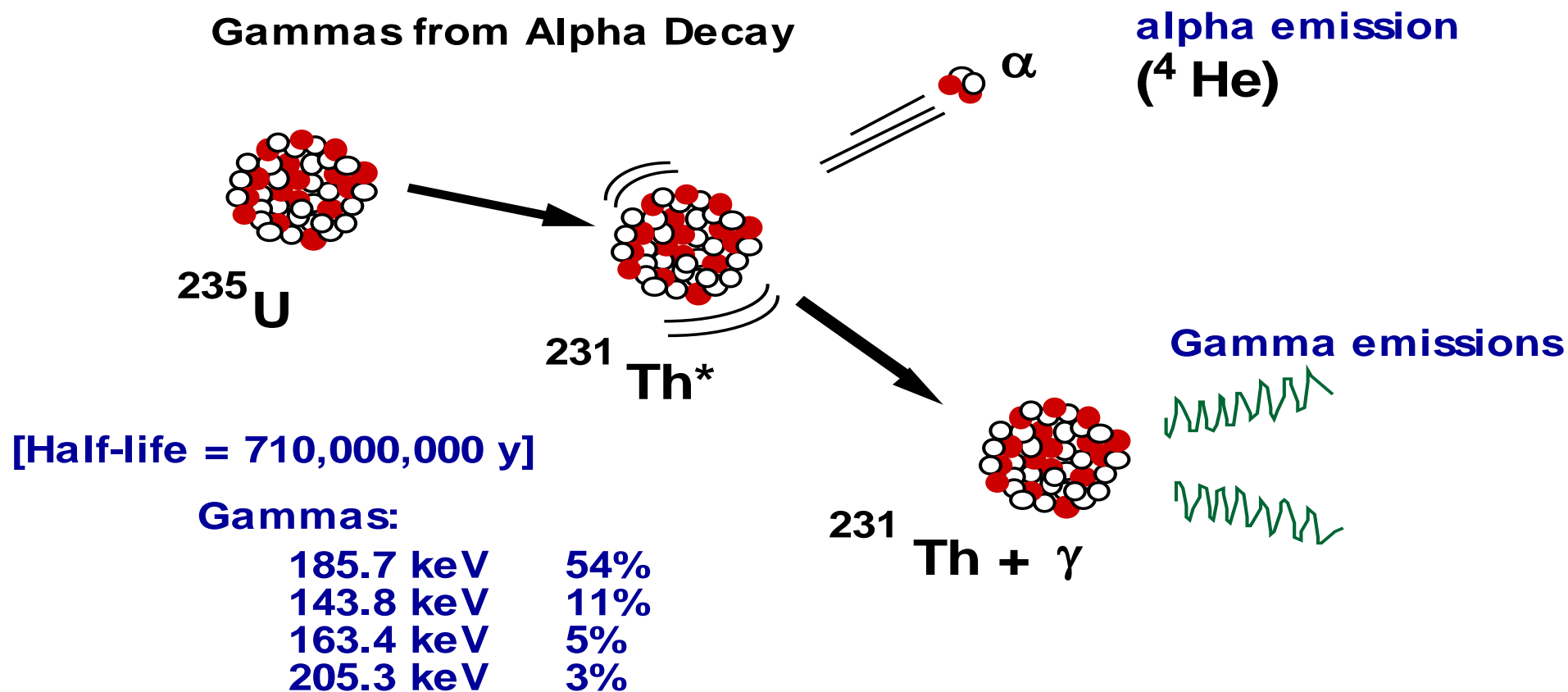




# Origin of $\gamma$ -rays

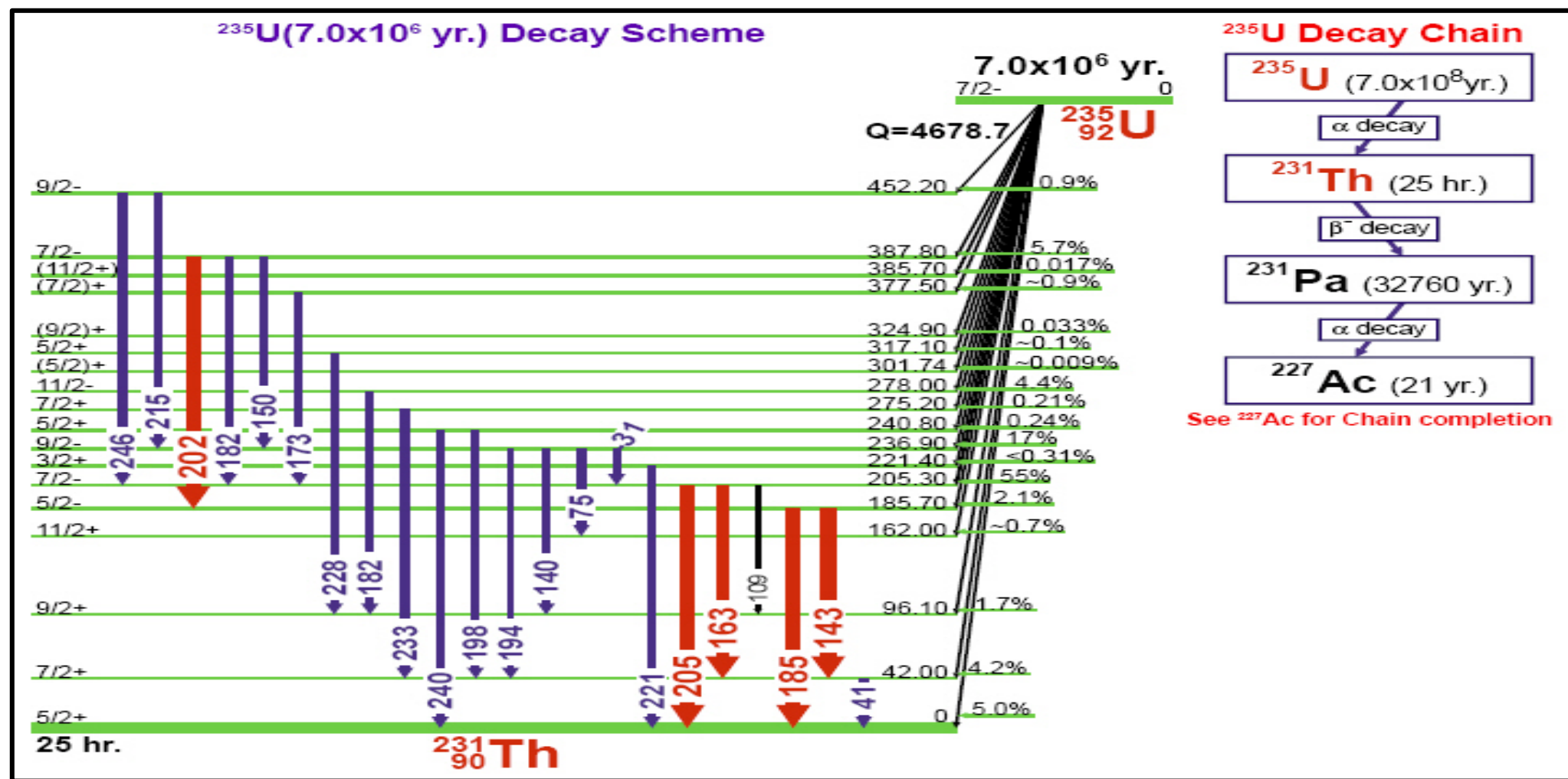
## GAMMA-RAY SIGNATURE

Gammas from Alpha Decay





# $^{235}\text{U}$ Decay Scheme and Branching Ratios



# Uranium Gamma-Ray Spectrum (300-keV Range)

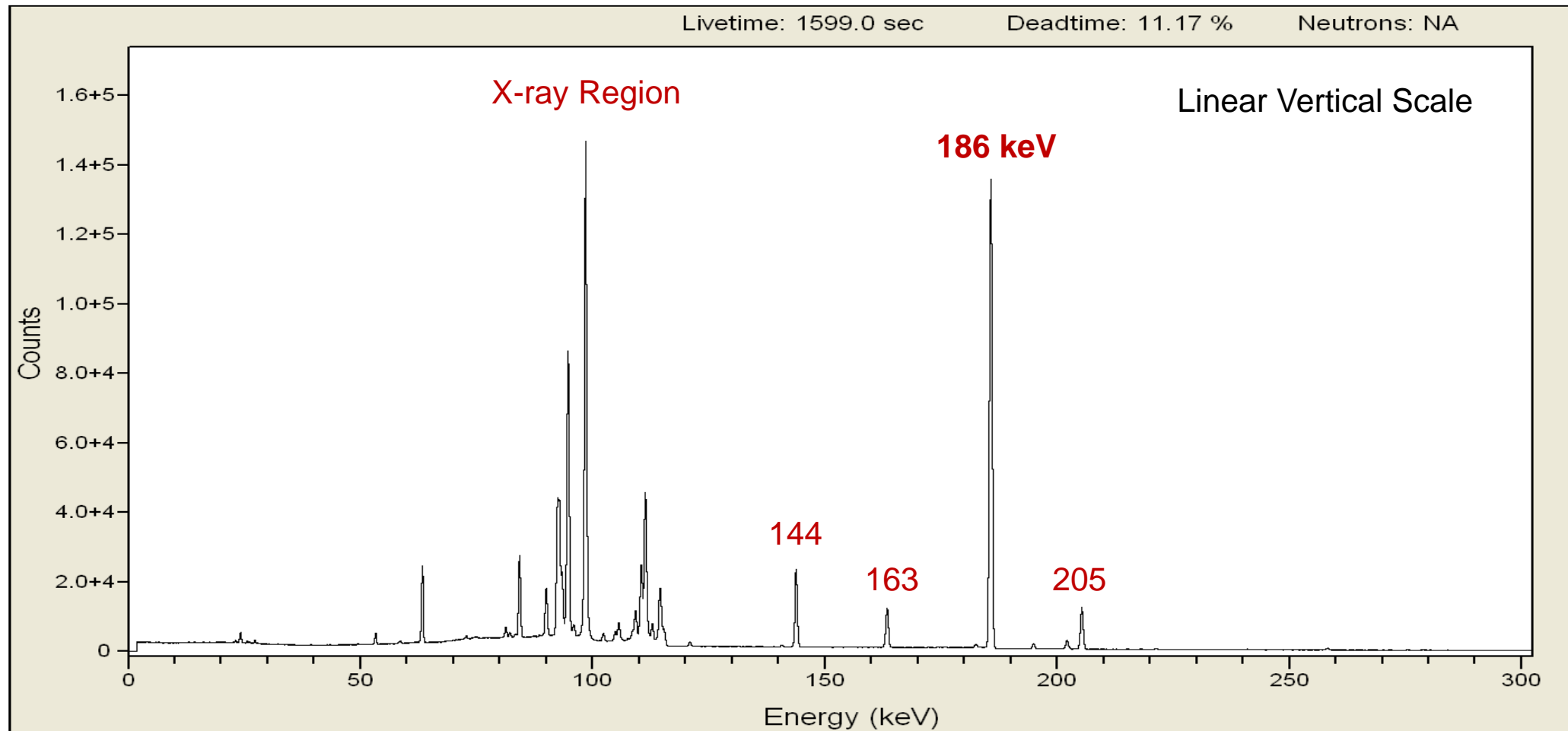


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# Uranium Gamma-Ray Spectrum (1-MeV Range)

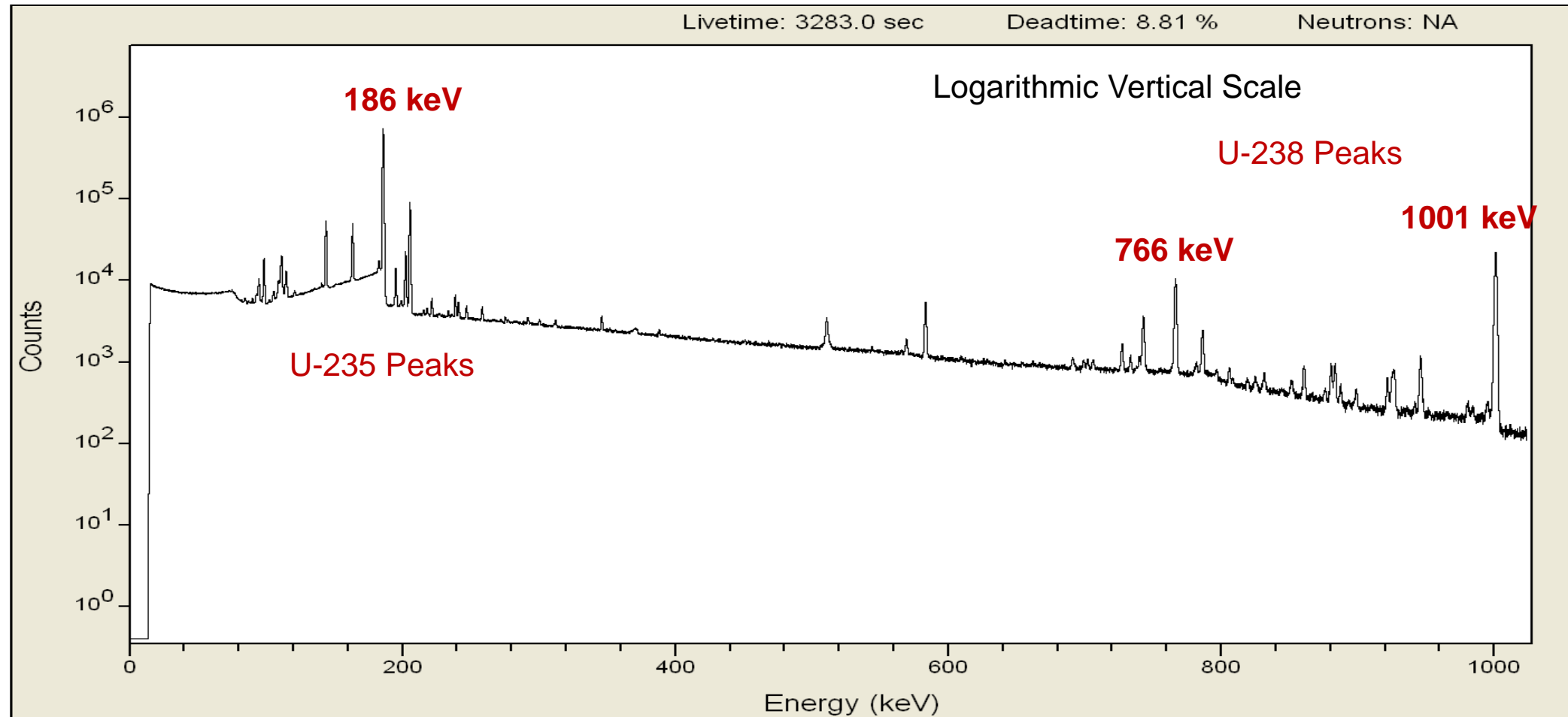


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# Plutonium Gamma-Ray Spectrum (1-MeV Range)

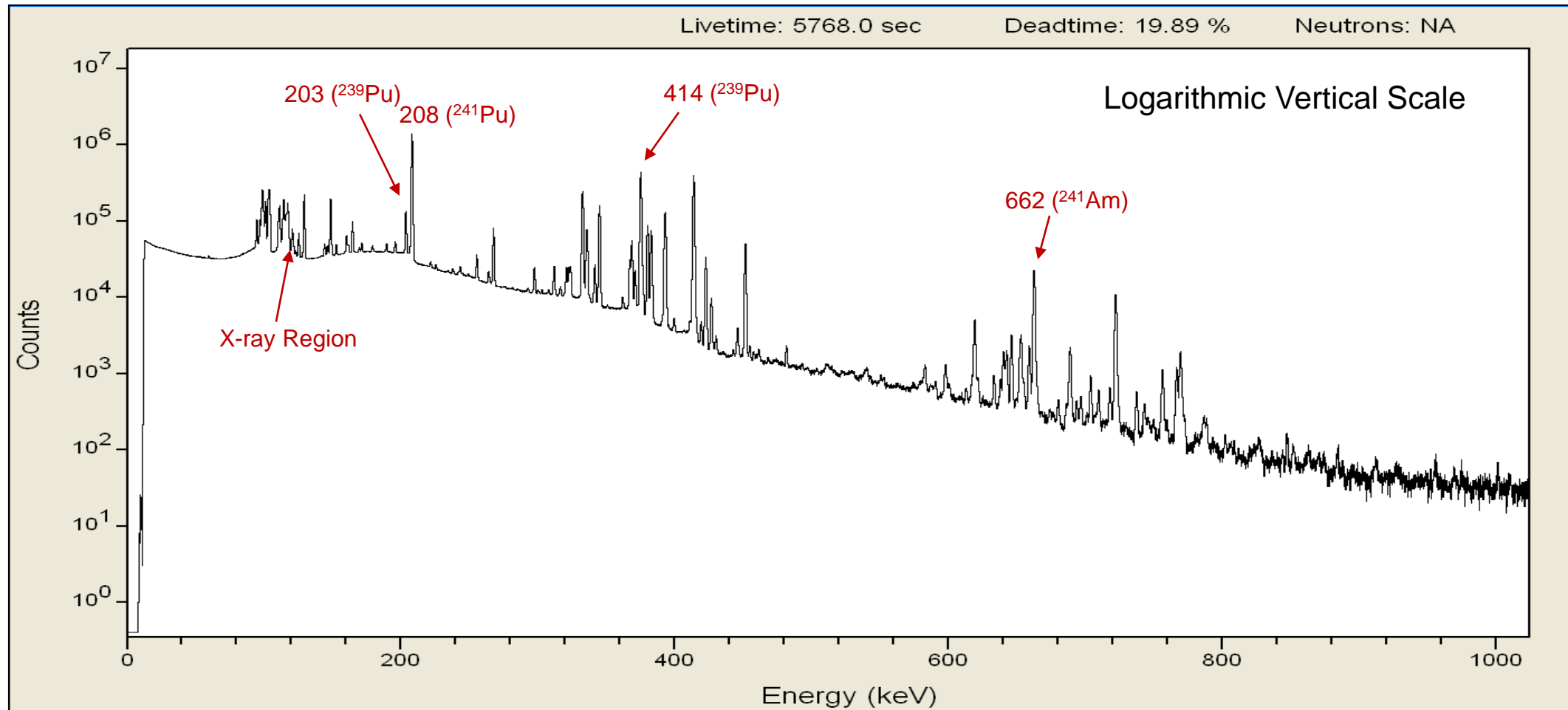


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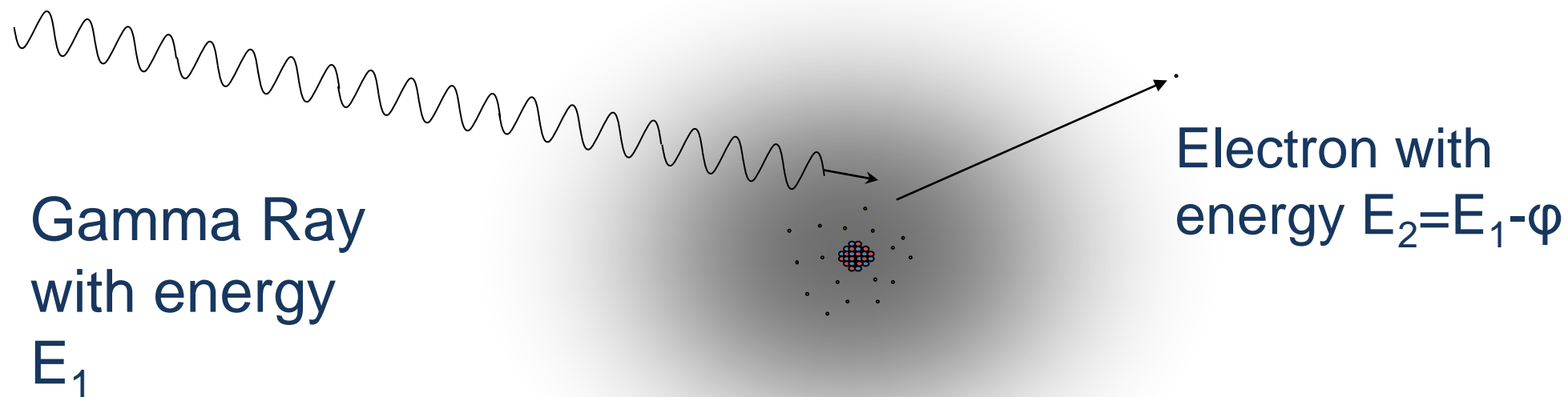


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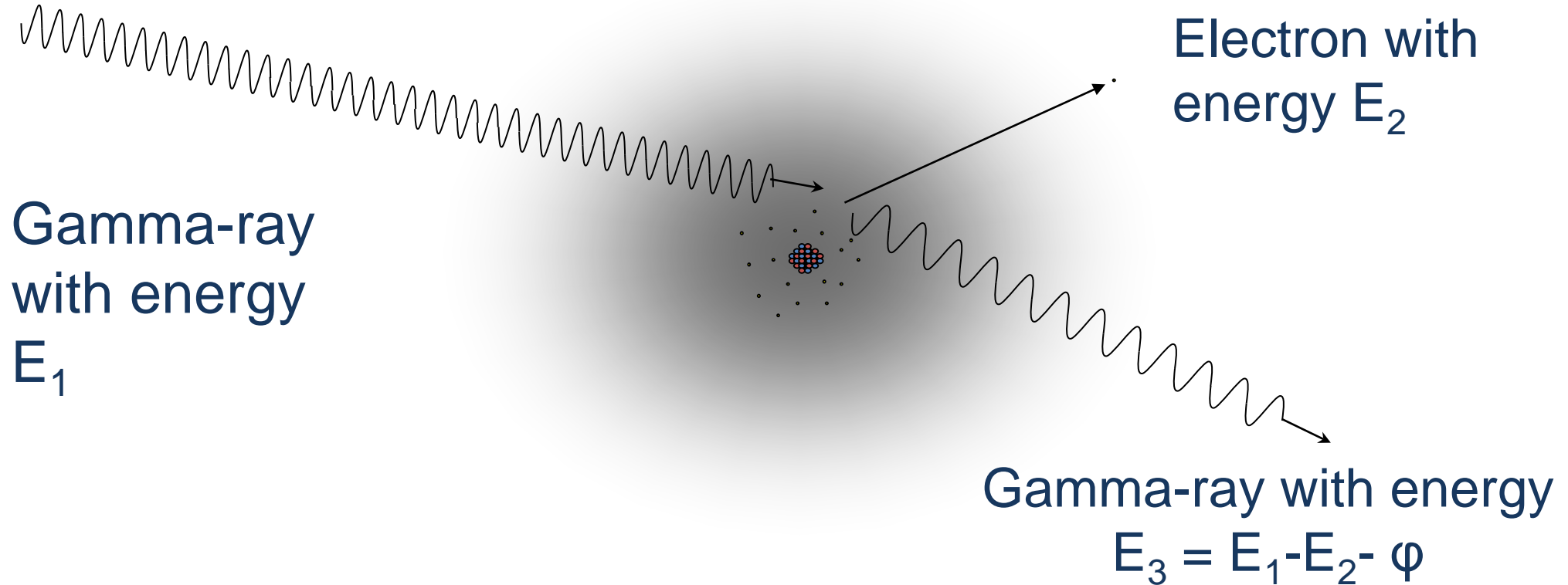


# The Photoelectric Effect



All of the gamma energy is absorbed in the interaction

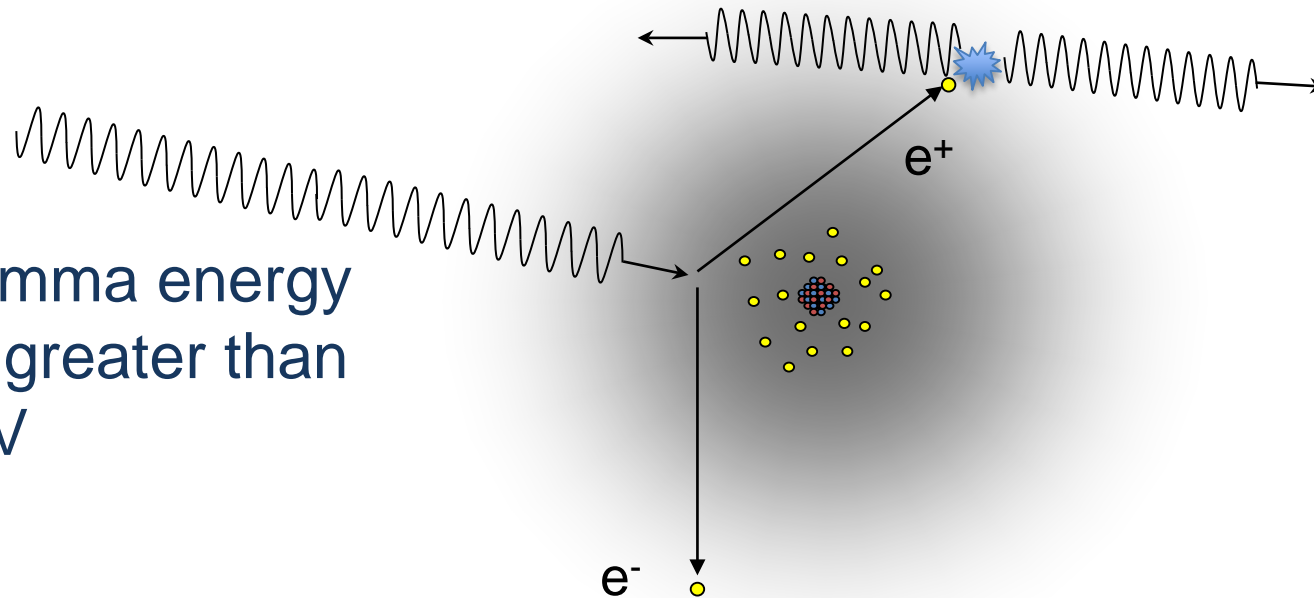
# Compton Scattering



# Pair Production and Annihilation

Positron annihilates in contact with an electron, producing two 511 keV gamma-rays

Initial gamma energy must be greater than 1022 keV





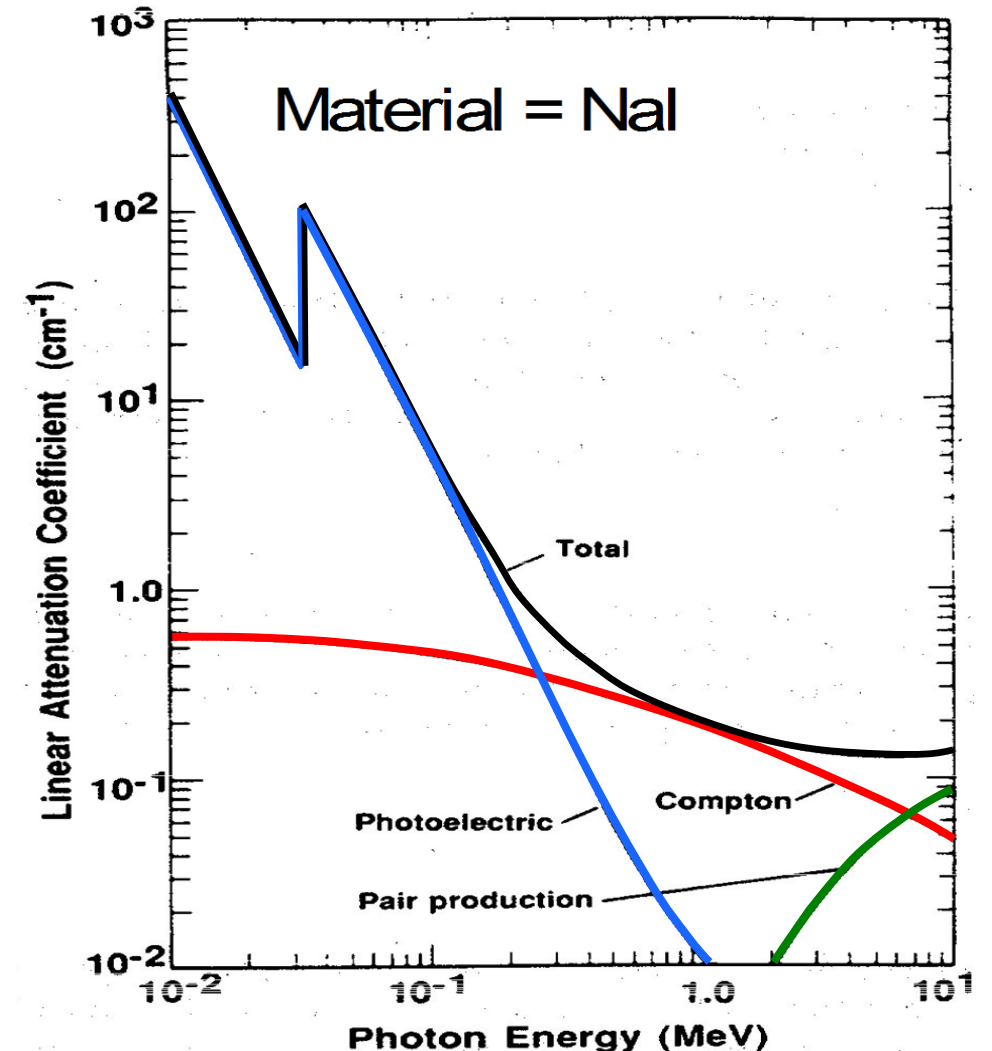
# Gamma-Ray Interaction Energy Dependence

The dominant interaction depends on the gamma-ray energy:

- Low Gamma Energy ( $E_\gamma$ ): **Photoelectric Effect**
- Medium  $E_\gamma$ : **Compton Effect**
- $E_\gamma > 1.022$  MeV: **Pair Production**

Linear Attenuation Coefficient depends on:

- Atomic number of the absorber,  $Z$
- Energy of incident gamma ray,  $E_\gamma$
- Density of the absorber,  $\rho$

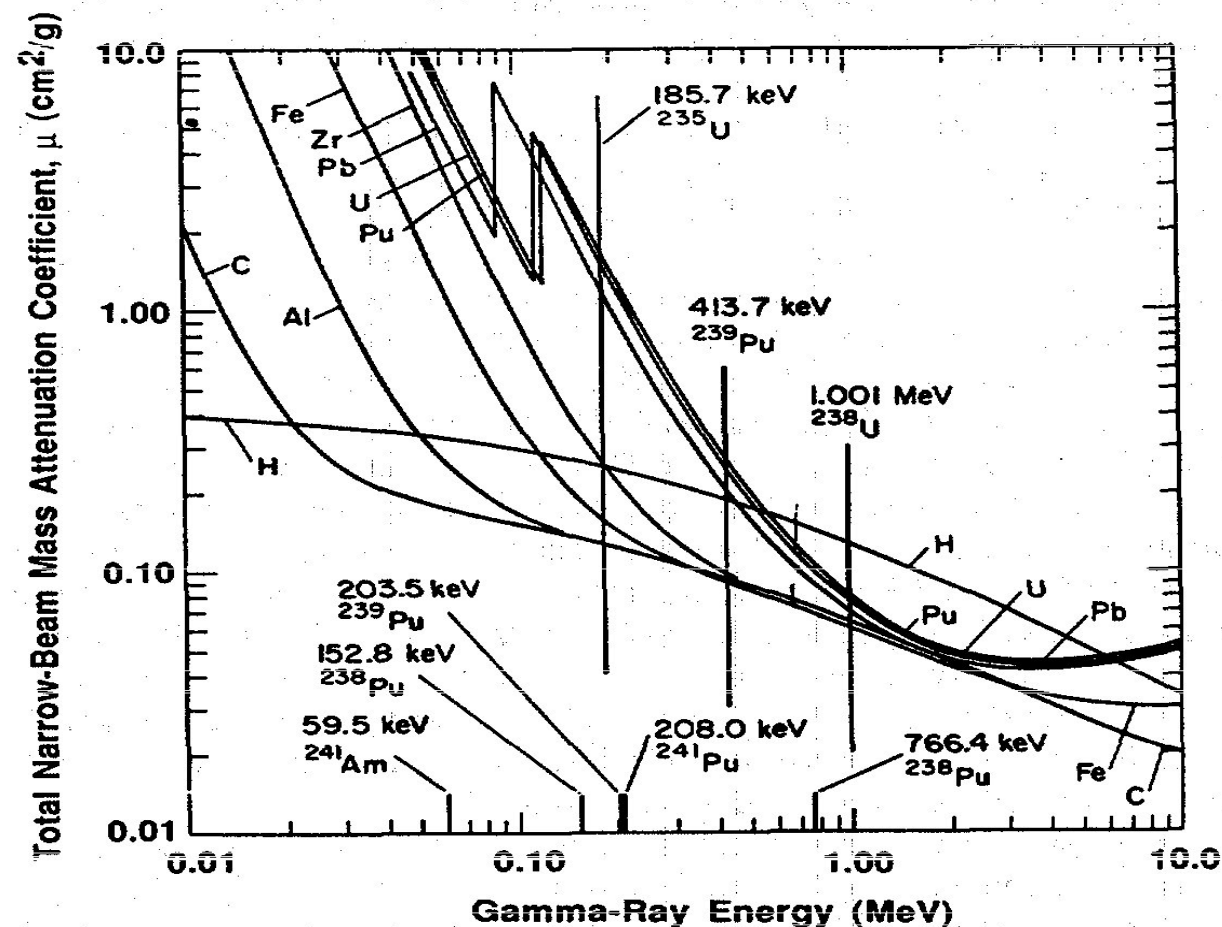




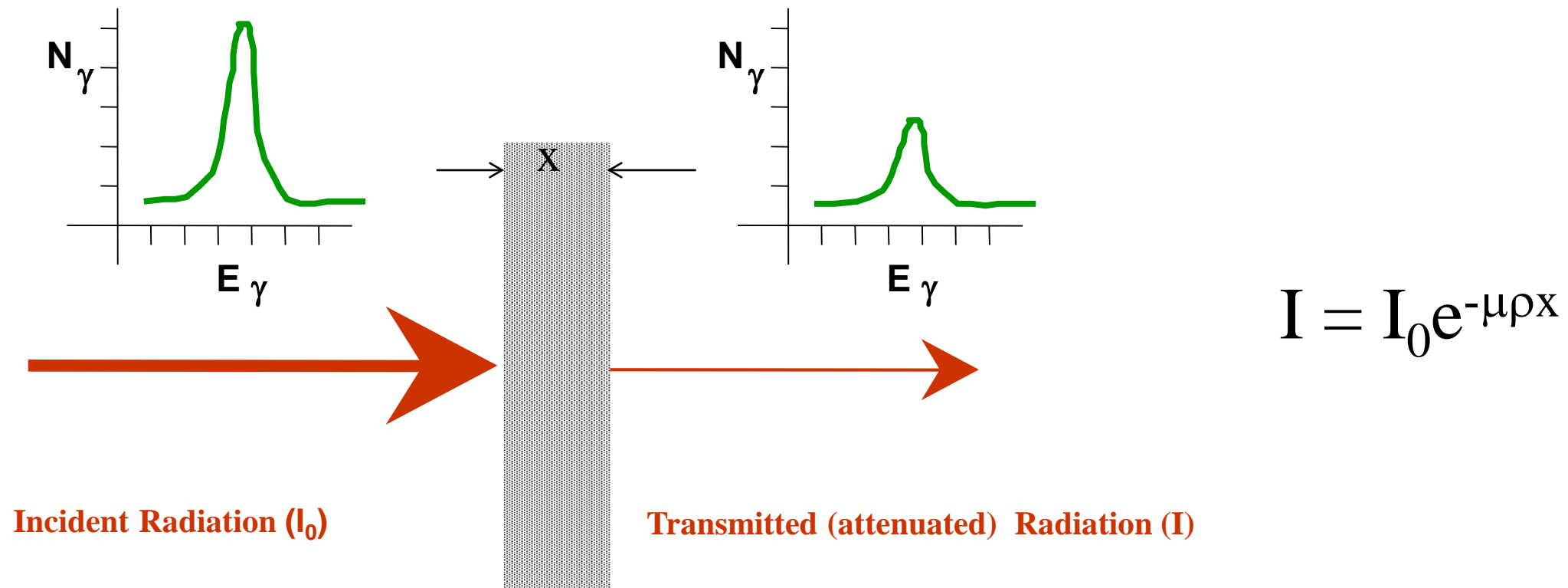
# Mass Attenuation Coefficient, $\mu/\rho \rightarrow \mu_Z(E_\gamma)/\rho$

## $\mu/\rho$ depends on:

- Atomic number of the absorber,  $Z$
- Energy of incident gamma ray,  $E_\gamma$
- But NOT on the density of the absorber,  $\rho$



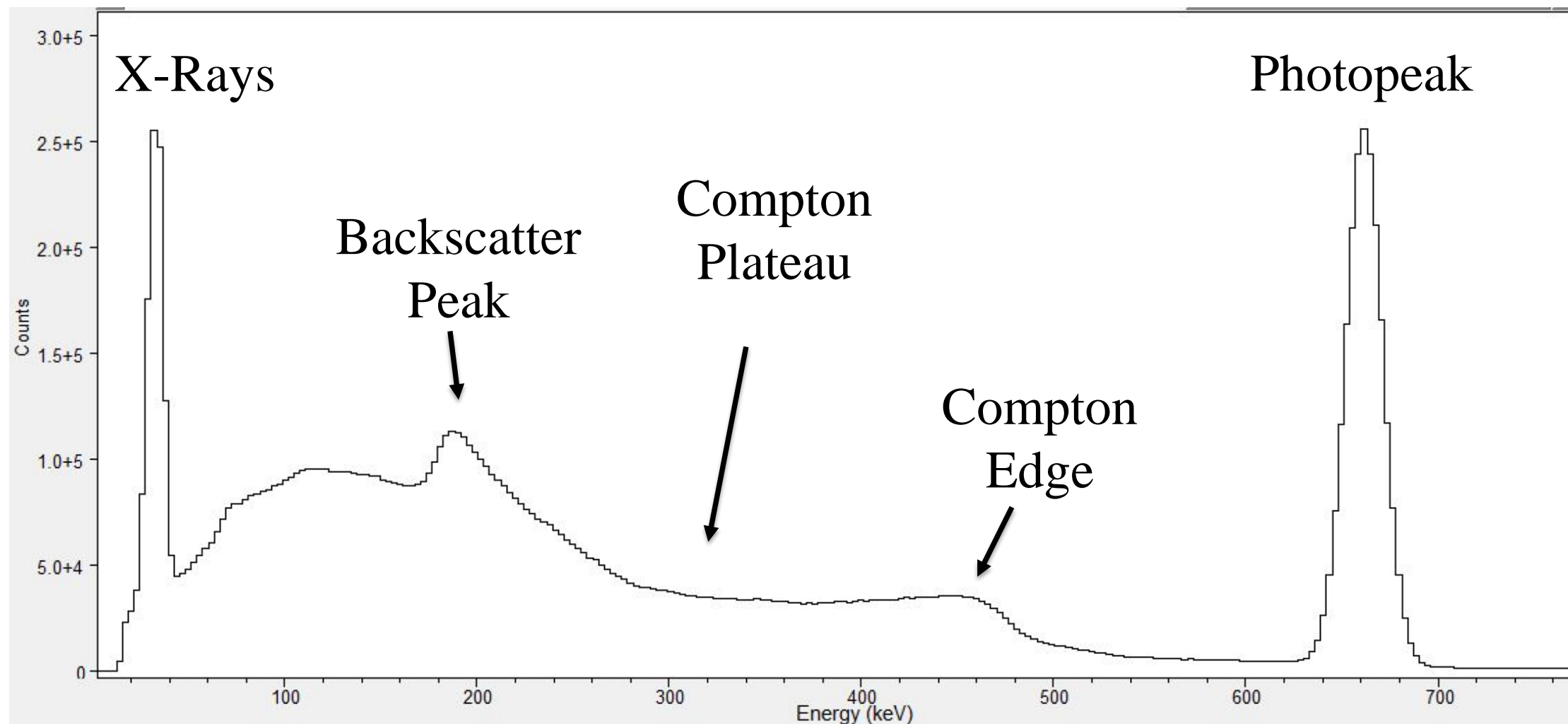
# Attenuation of Gamma Rays



Transmission,  $T = I/I_0 = e^{-\mu \rho x}$



# Features of a Monoenergetic Spectrum



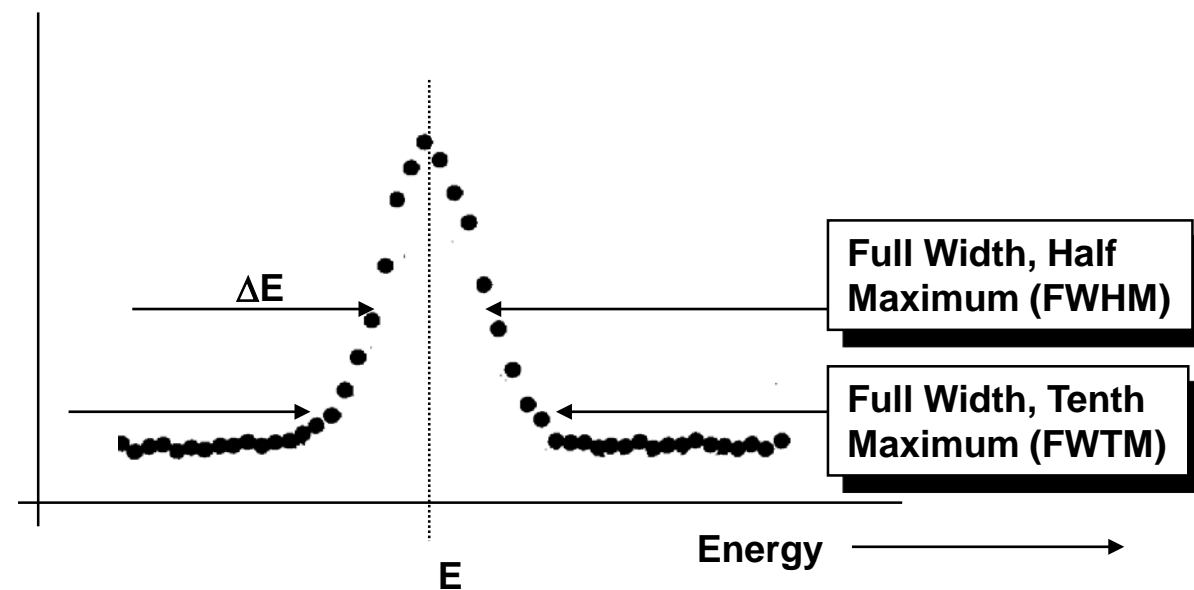
## Detector Parameters

- Resolution: how precisely can the detector determine the gamma ray energies?
- Efficiency: how many of the available gamma rays are actually detected?
- Efficiency curve: how efficient is the detector at various energies?
- Dead time: in a given measurement period, how much of the time can the detector actually respond to gamma rays?

# Energy Resolution

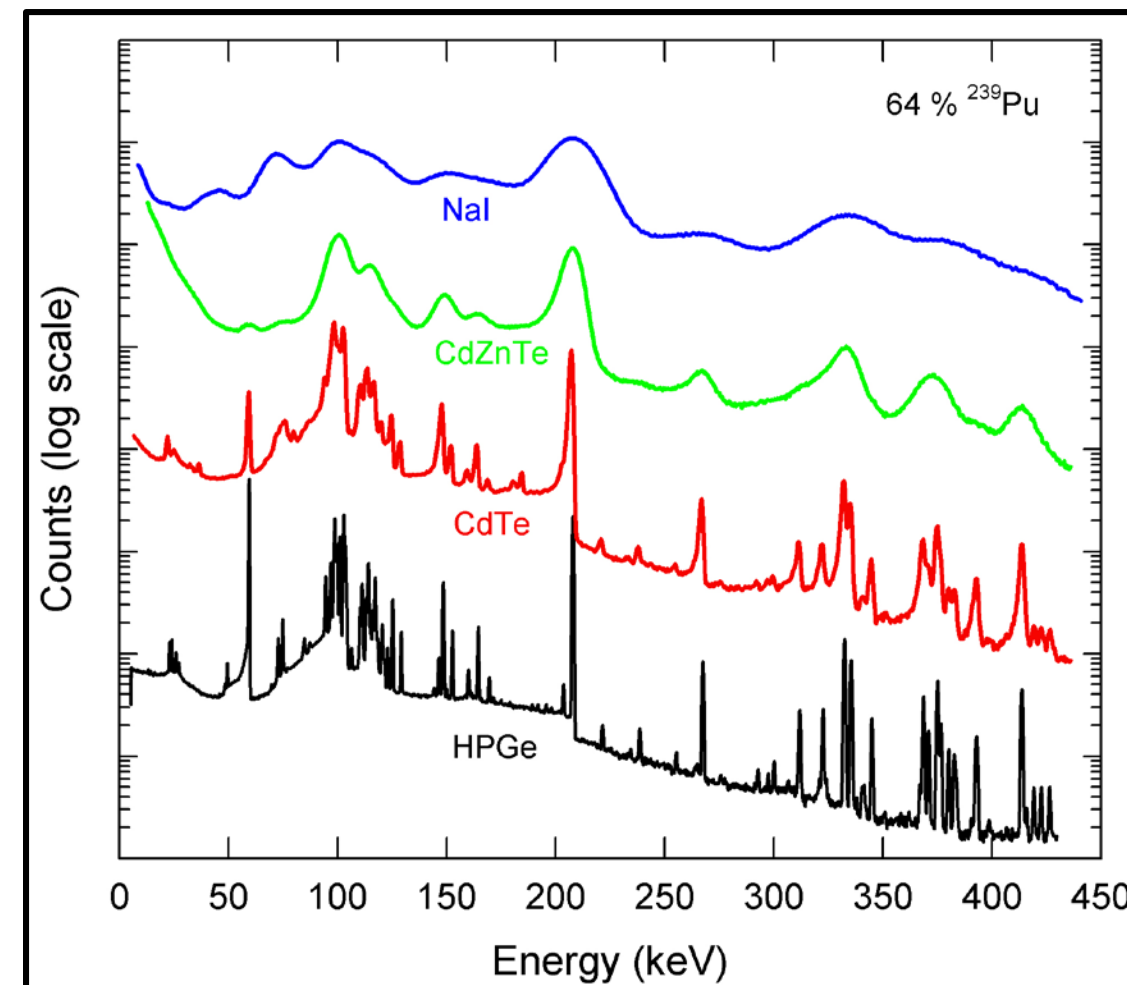
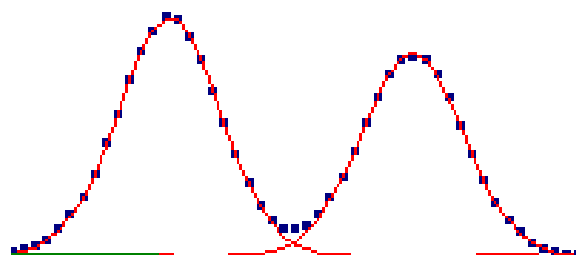
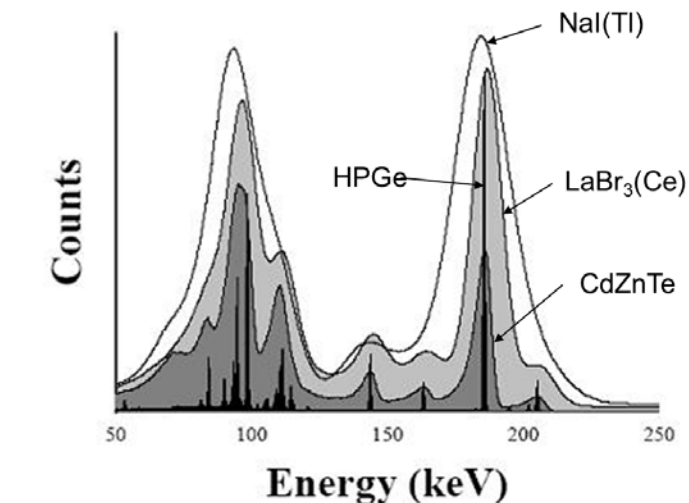
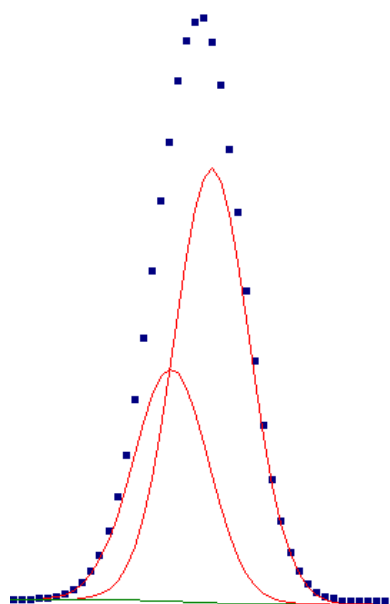
- Resolution is defined by the *full width at half max (FWHM)*
- For a Gaussian peak,  $FWHM=2.35\sigma$

Detector	Typical Values		FWHM/E
	FWHM	E	
Nal(Tl)	29 keV	661 keV	7.5%
Nal(Tl)	150 keV	1332 keV	10.6%
Ge (Planar)	540 eV	122 keV	0.44%
Ge (Coax)	1.75 keV	1332 keV	0.13%



# Energy Resolution

A spectrographic system's energy resolution determines how far apart peaks have to be to be resolved



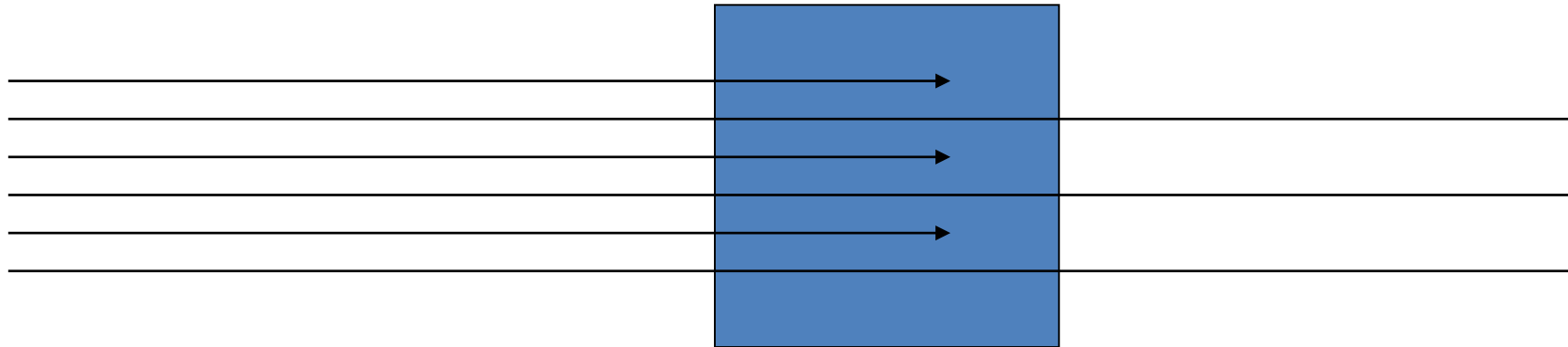
# Factors that Affect Resolution

- The detector type (NaI, Ge, CZT,...)
- Radiation damage to the detector
- The measurement environment
  - Radiation
  - Electronic
  - Physical (vibrations, temperature, humidity,...)
- Measurement electronics
- Quality
  - Settings (pole-zero, baseline restoration, time constants, pileup rejection, count rates,...)
  - Placement (near electronic sources, near other radiation fields, ...)



## Detector Parameters - Efficiency

- 50% efficiency is illustrated here

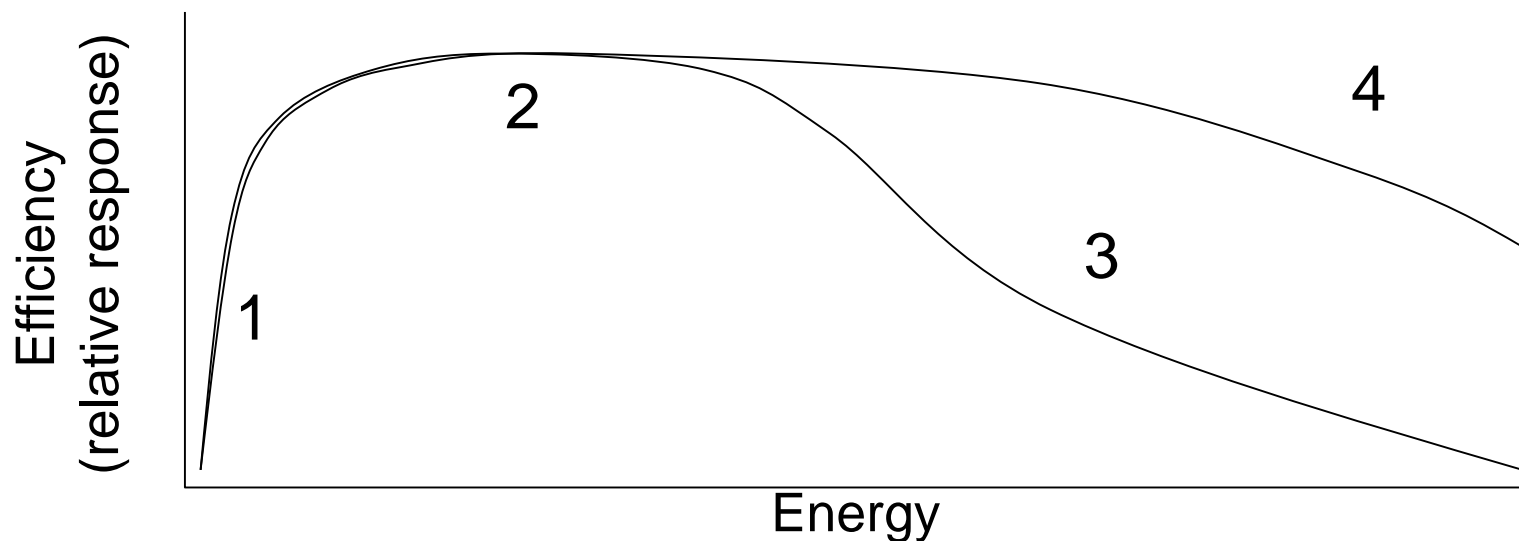


- Note: relative efficiency is often used; this compares a detector's efficiency to that of a 3" by 3" sodium iodide detector



## Detector Parameters - Efficiency

1. Very low energy rays can have difficulty penetrating to the crystal
2. Moderate energy rays are generally fully absorbed
3. High energy rays can go through the entire crystal
4. Larger detectors have better high-energy efficiency

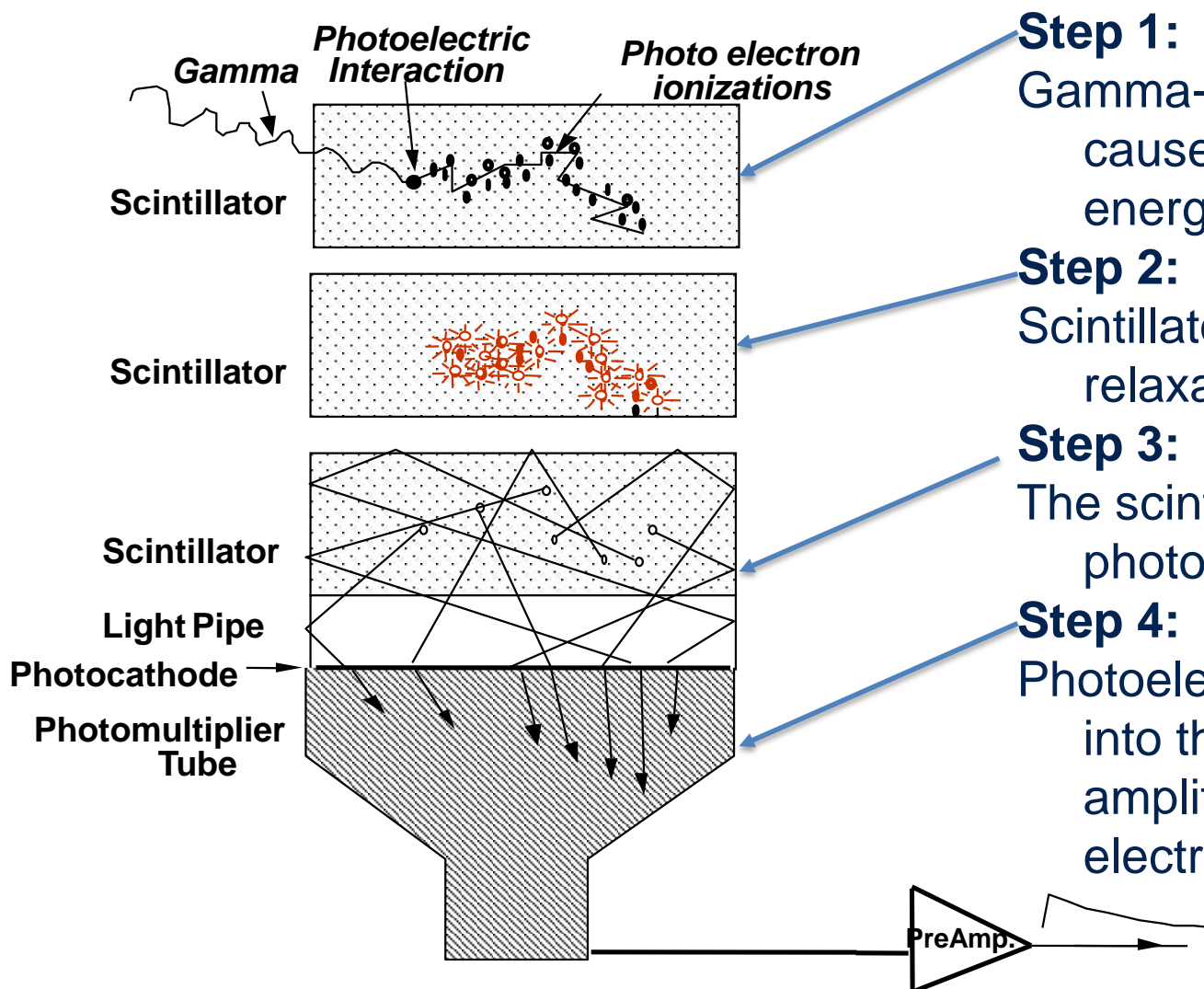


# Detector Technologies

- Scintillators
  - Sodium Iodide, NaI(Tl)
  - Lanthanum Bromide, LaBr<sub>3</sub>(Ce)
- Semiconductors
  - Cadmium Zinc Telluride (CdZnTe)
  - High Purity Germanium (HPGe)



# Nal Scintillation Detector



## Step 1:

Gamma-ray **generates a photoelectron which** causes ionization/excitation proportional to energy **deposited**

## Step 2:

Scintillator atoms emit light after recombination and relaxation to lower energy states

## Step 3:

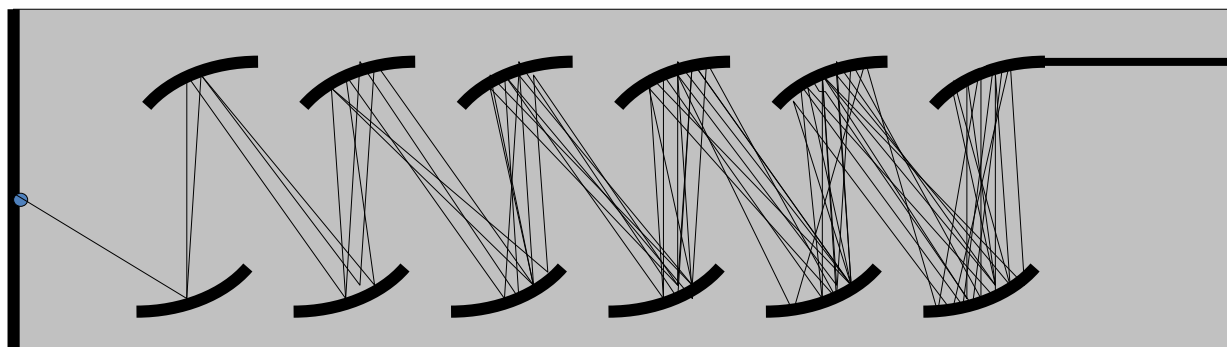
The scintillation light is collected by the photocathode.

## Step 4:

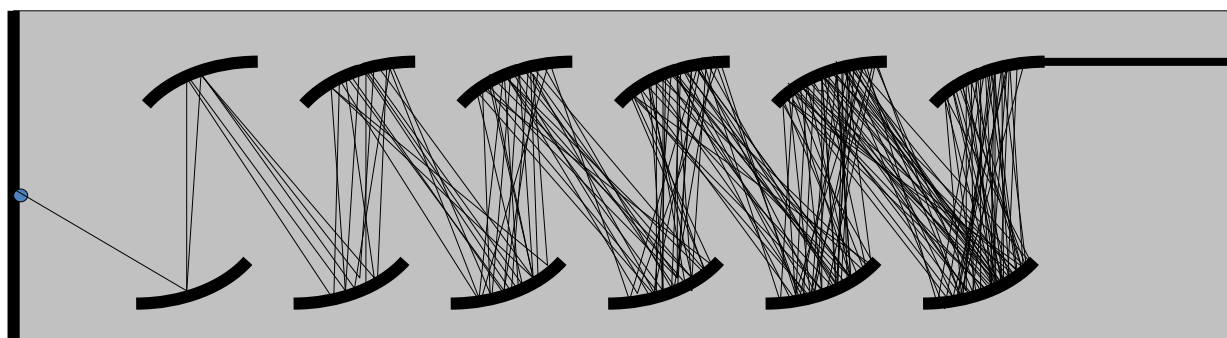
Photoelectrons are emitted from the photocathode into the phototube dynode chain where they are amplified and then sent to the pulse processing electronics.



# Photomultiplier Tube (PMT)



Low Voltage  
1:12



Higher Voltage  
1:40

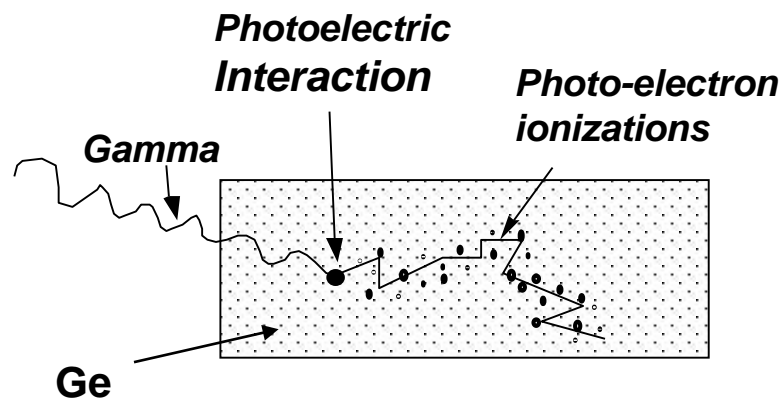
Photomultipliers are temperature sensitive; warming or cooling of the system will shift the peaks in the spectrum.

# Nal(Tl) Detectors

- Nal(Tl) is dense and has high effective Z, so it effectively stops gamma rays; this gives good overall efficiency
- Efficiency depends on the size of the crystal and the energy of the gamma ray
- Nal(Tl) crystals are shock sensitive
- Nal(Tl) crystals must be sealed against moisture
- Nal(Tl) detectors have significant gain shift with fluctuating temperatures
- Nal(Tl) detectors are considered low resolution detectors
  - Resolution is ~half of LaBr<sub>3</sub>(Ce), and ~0.1x that of HPGe

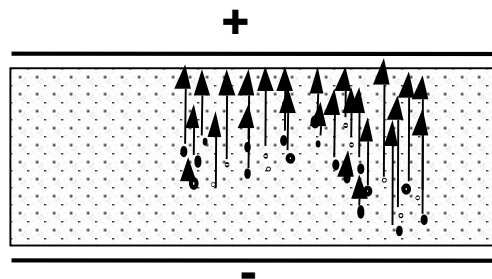


# High Purity Germanium (HPGe) Detector



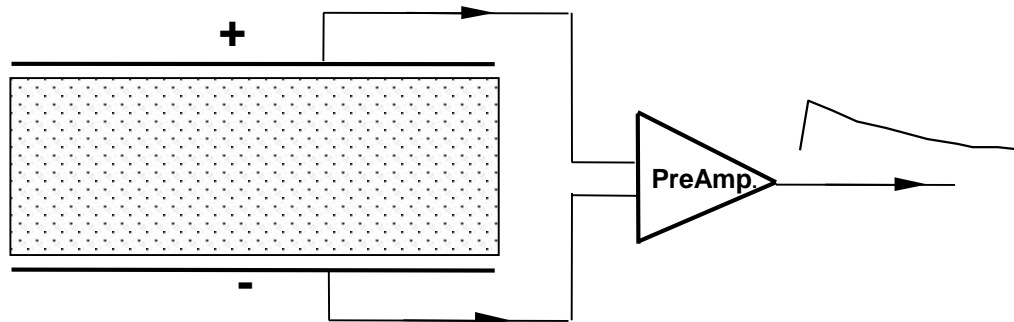
## Step 1:

Gamma-ray causes ionization (electron-hole pairs) proportional to energy **deposited**



## Step 2:

Electrons move toward the positive electrode while holes move toward the negative electrode

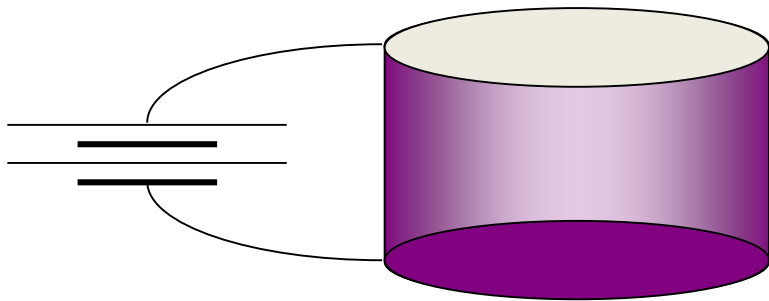


## Step 3:

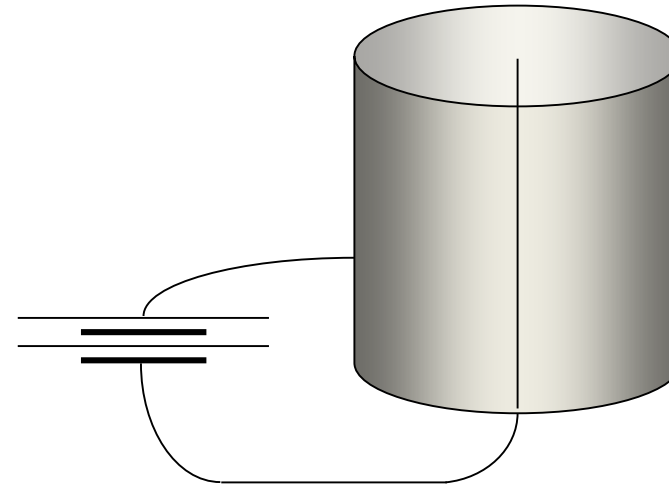
The charge burst is converted into a voltage pulse by a preamplifier. The pulse is proportional to the energy of the gamma ray.

# Germanium Detectors

There are two contacts on the detector, and a high voltage is applied.



Planar detector; better resolution, lower efficiency

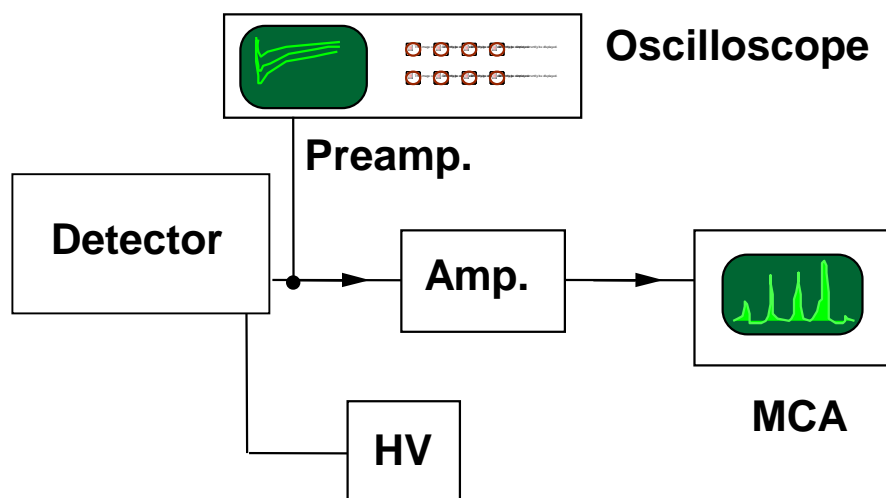


Coaxial detector; poorer resolution, better efficiency





# Gamma-Ray Spectroscopy Instrumentation

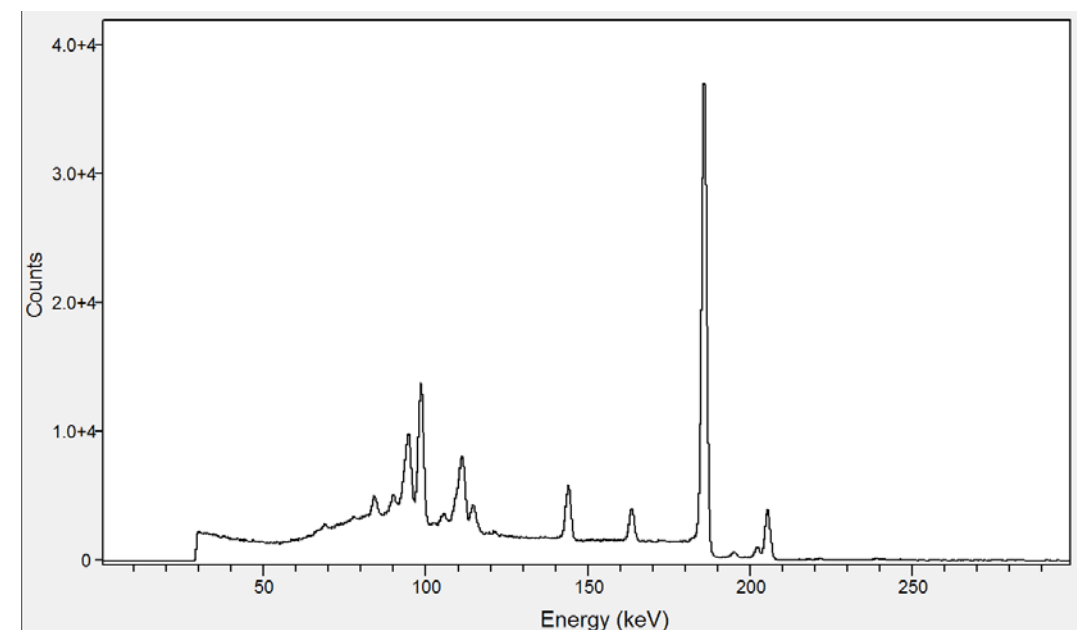
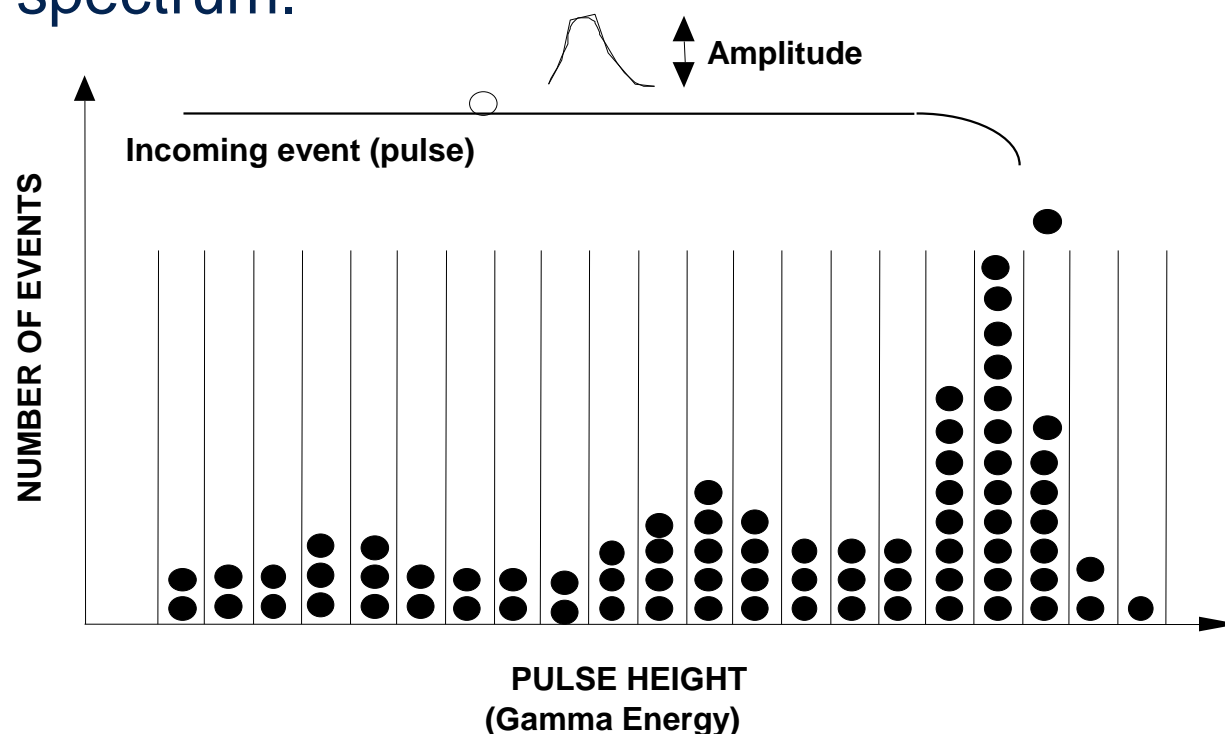


- Battery-powered
- Computer-based
  - data acquisition
  - data analysis
- Commercially available



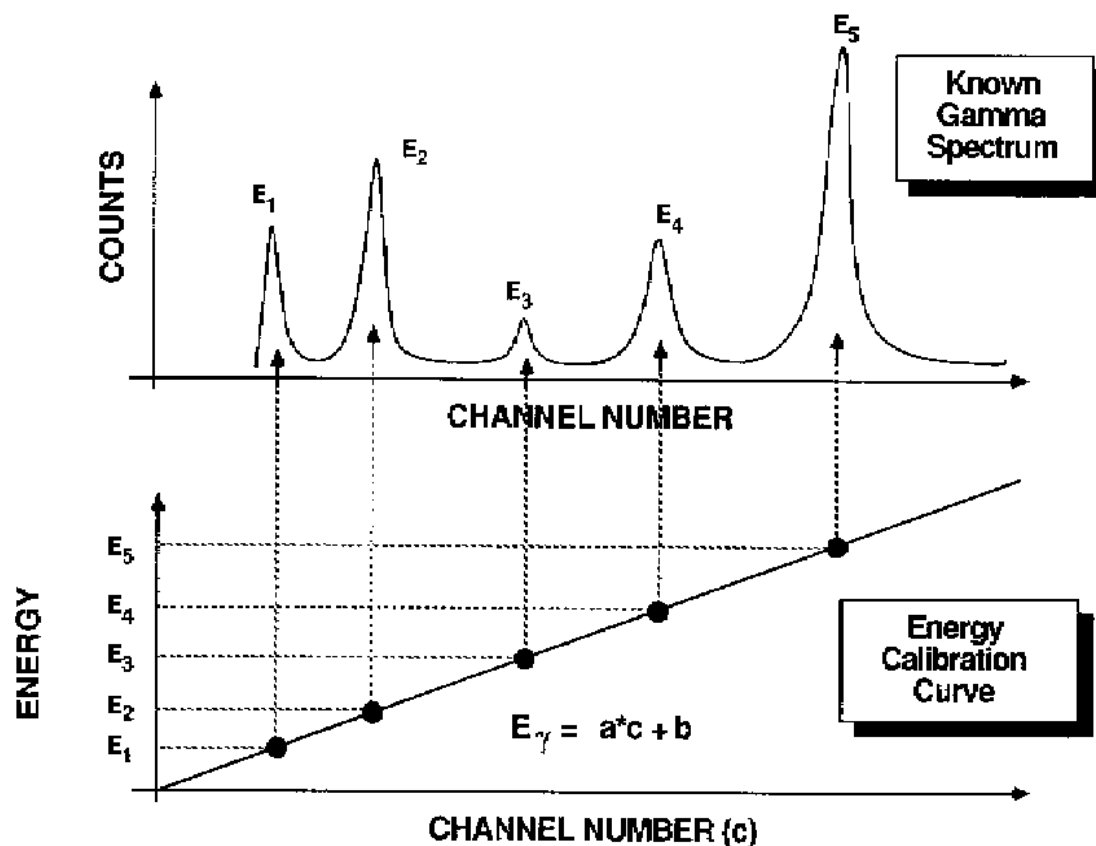
# From Voltage Pulses to a Spectrum

The Multi-Channel Analyzer (MCA) electronically sorts voltage pulses of different amplitudes into “bins” which correspond to the energy deposited in the crystal by each gamma ray. This forms a pulse-height or gamma ray energy spectrum.





# Energy Calibration



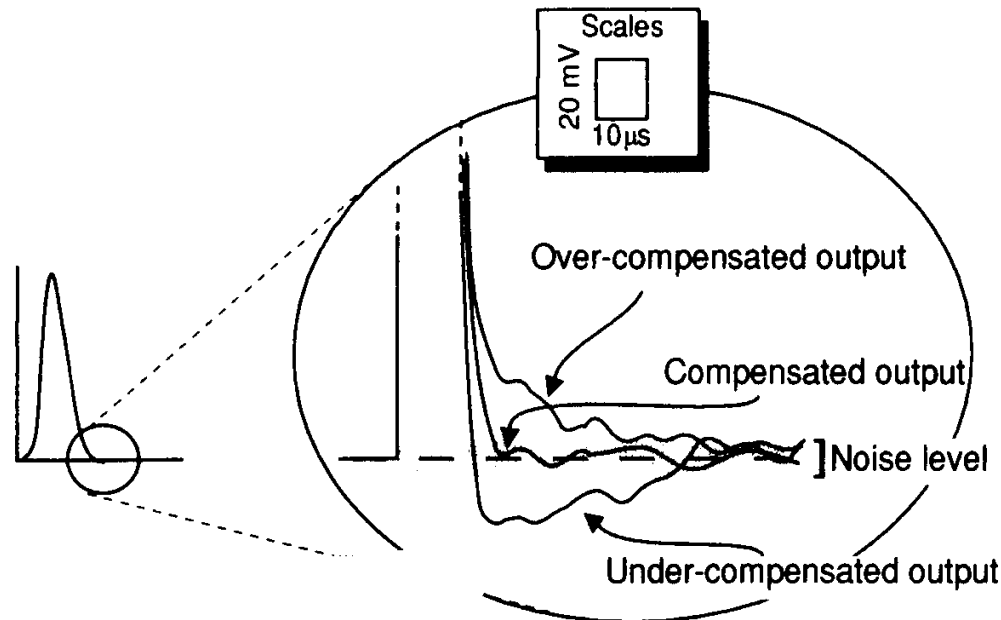
$$E_\gamma (\text{keV}) = A \cdot \text{Channel\#} + B$$

Energy accuracy to about 0.5 keV usually possible

- HPGe and LaBr<sub>3</sub>(Ce) have very linear calibrations with small offsets (B)
- NaI(Tl) has an approximately linear calibration with a larger offset

# Amplifier Pole-Zero (PZ) Compensation

- Pre-amplifier pulse input into the amplifier is a pulse with a long decay time. Consequently, the output from the amplifier is a pulse that exhibits an undershoot below zero baseline and has a long recovery time. If another pulse arrives before recovery, its amplitude will be in error.
- Pole-zero compensation is a technique by which the undershoot is avoided by adding a resistance in parallel to the capacitor in the differentiator-integrator (CR-RC) network of the amplifier. The value of the resistance is adjusted to compensate for the undershoot.

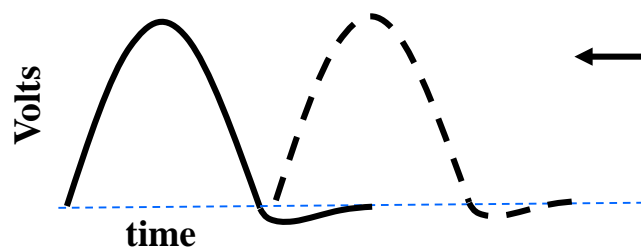


- PZ adjustment is the first step in attempting to correct bad resolution and asymmetrical peaks
- Poor PZ settings can worsen resolution, increase deadtime, and shift the spectrum nonlinearly

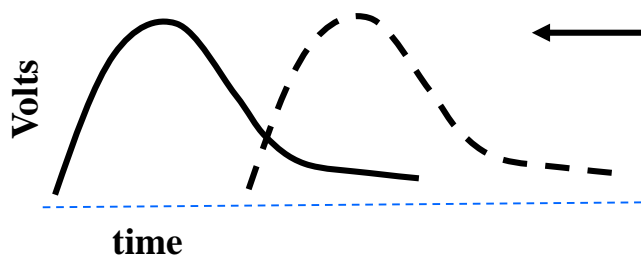


# Pole-Zero and Peak Shape

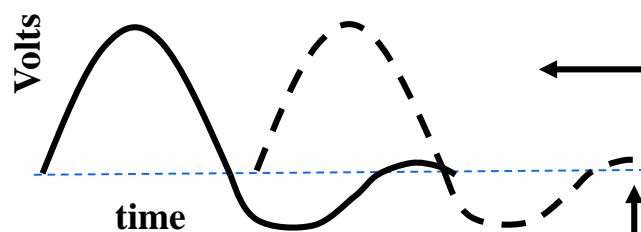
## Amplifier Pulses



← Proper pole-zero:  
negligible tailing  
unless very high count  
rates →



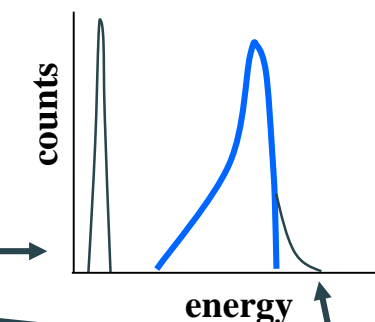
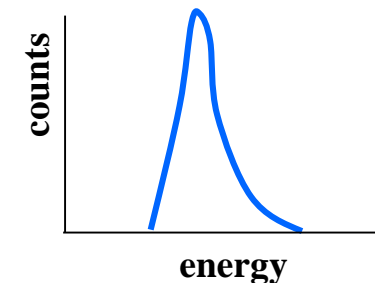
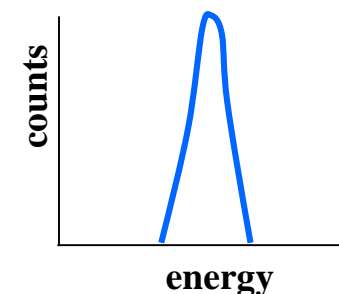
← Undershooting the baseline: **high energy tailing** →



← Overshooting the baseline:  
**low energy tailing** →

← Oscillation: Low E spike and  
or high E tailing →

## Peaks in Spectrum



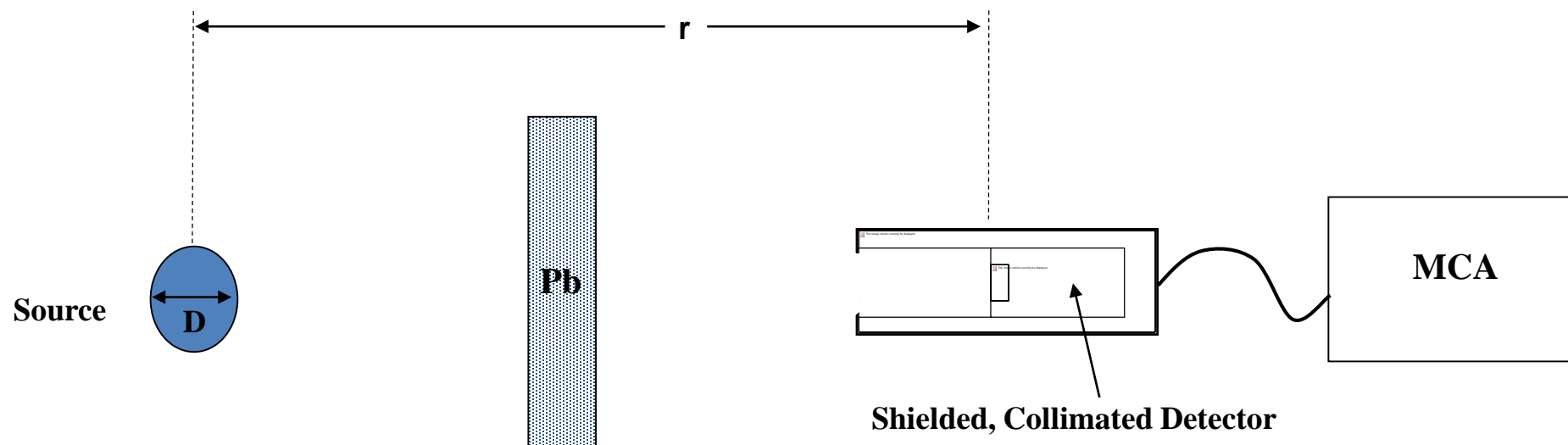


# Factors that Affect Gamma-Ray Data

- Activity and configuration of the source
- Distance
- External and internal attenuation
- Collimation
- Detector efficiency
- Electronics processing

Distance Formula

$$Rate = K \cdot \frac{Mass}{r^2} \quad (for \ r \gg D)$$



# The Limit of Measurement Precision

**Even if you have PERFECT:**

- education of the operator
- management of the item and background
- execution of the measurement

**You still have:**

- uncertainty as to how close *your* result is to the true result

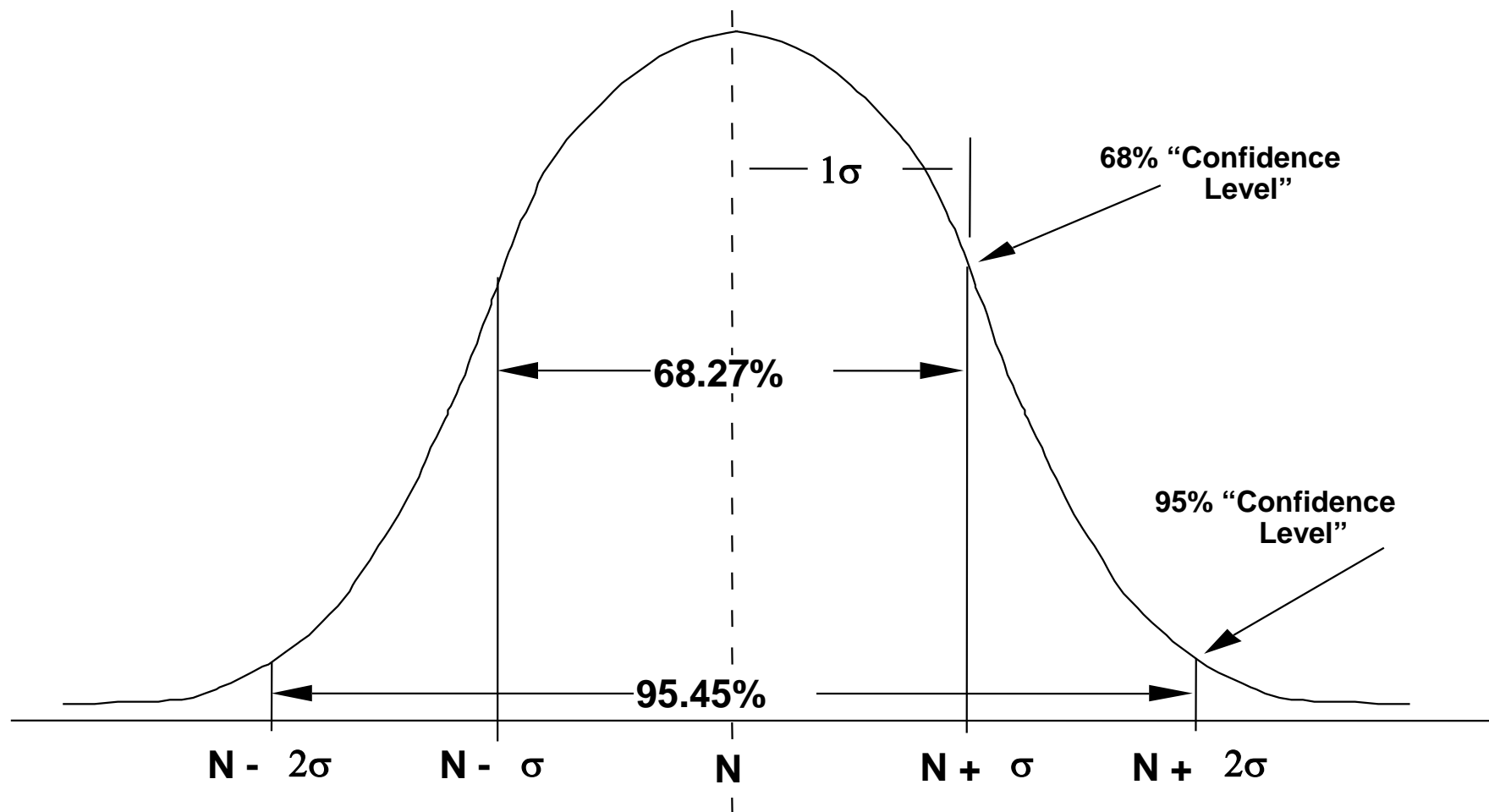
**STATISTICAL uncertainty can not be removed**

It is a fact of nature!

as a minimum value determined by statistics of the process



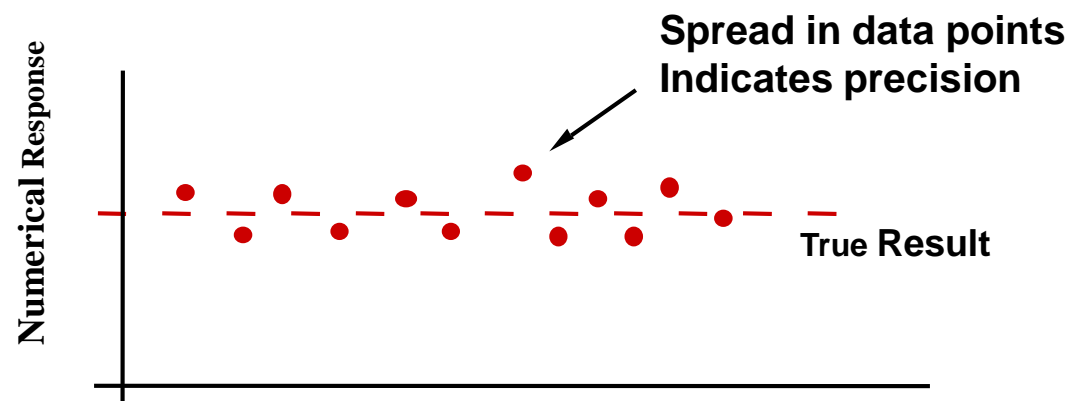
# Gaussian (Normal) Distribution





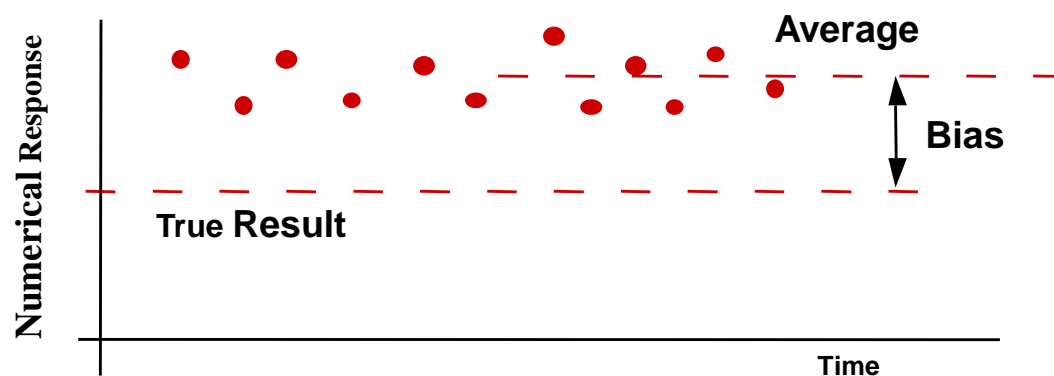


# Precision versus Bias



## Measurement Precision:

The degree to which repeated measurements of the same item give the same results.



## Measurement Bias:

The amount by which the average of many measurement results of the same standard differs from the true measurement value for that standard.



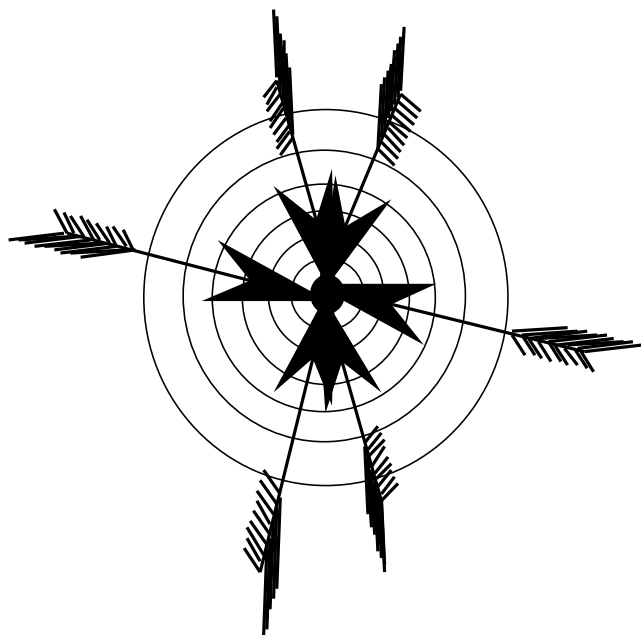
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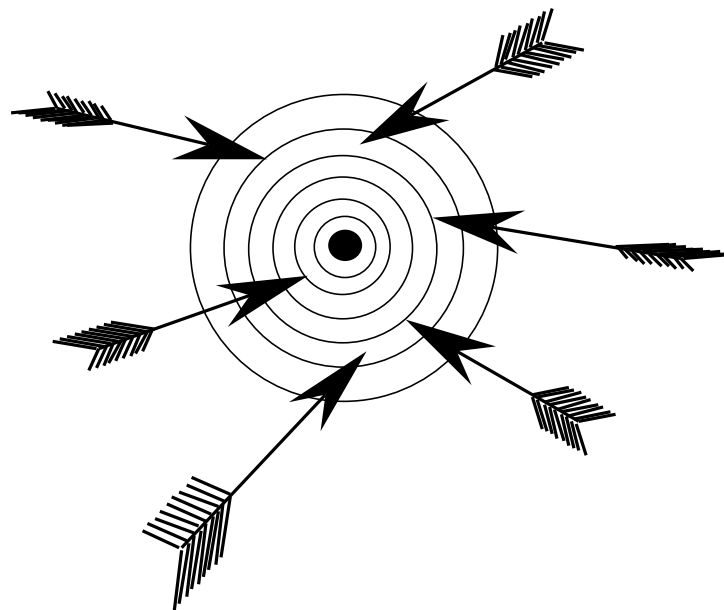


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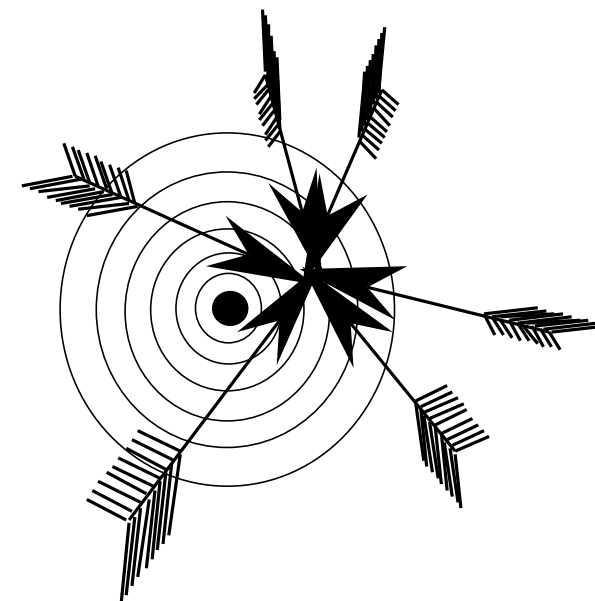
# Precision, Accuracy, and Bias



**Good precision,  
good accuracy**



**Poor precision,  
indeterminate accuracy**

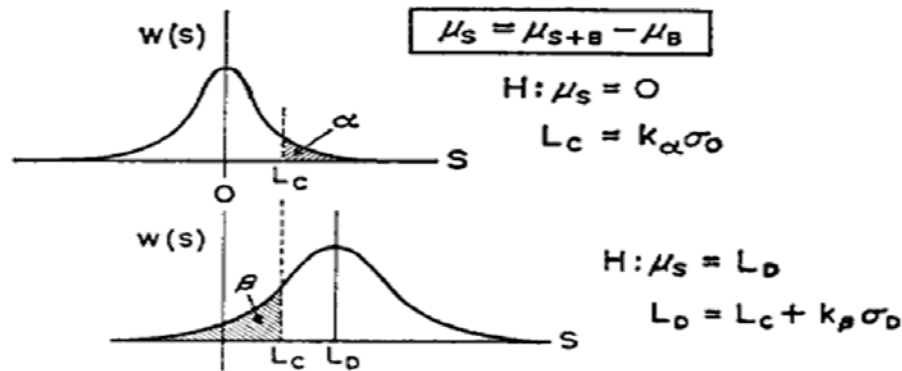


**Good precision, poor  
accuracy  
(biased measurement)**

# Uncertainty in Nuclear Counting

- For a measured number of counts, **N** from a random nuclear decay process
  - the standard deviation is  $\sigma = (\mathbf{N})^{1/2}$
  - the RELATIVE standard deviation is  $\sigma_R = \sigma/N = 1/(\mathbf{N})^{1/2}$
- Since the number or counts, **N**, is in the denominator of the relative standard deviation,  $\sigma_R$  can be reduced by
  - taking more data
  - Increase the measurement time
  - Use a source of higher activity
  - Decrease the distance between detector and source as long as you still observe the “point-source” criterion

# Critical Limit and Detection Limit – The Currie approach



Assuming  $k_\alpha = k_\beta = k$ , it can be shown that:

$$L_D = k^2 + 2 \cdot L_C$$

or

$L_D = k^2 + 2 \cdot k \cdot \sqrt{2 \cdot \sigma_B^2}$  which is the familiar form of the Currie equation for detection limit.

**Hypothesis testing:  $\alpha$  is deciding that the substance is present when it is not;  $\beta$  is failing to decide that the substance is present when it is.**

Source: Lloyd A. Currie, "Limits for Qualitative Detection and Quantitative Determination: Application to Radiochemistry," pp. 586–93, *Analytical Chemistry* **40** (3), 1968 (DOI: 10.1021/ac60259a007).

# Review and Summary of the Enabling Learning Objectives



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- Describe the origin of x-rays and gamma-rays, the radioactive decay characteristics for uranium and plutonium and resulting photon emission yields.
- Explain how gamma-rays interact with matter: photoelectric effect, Compton scatter, pair production and annihilation, attenuation.
- List features specific to a uranium and plutonium gamma-ray spectrum
- Describe detector parameters: resolution, efficiency, dead-time
- Recognize detector technologies: scintillators and semiconductors.
- Explain how gammas interact with a detector to create a spectrum, and the electronic settings that may be adjusted in the course of calibration: energy, pole-zero, integration time.
- Understand gamma-ray spectrometry statistical concepts for precision and bias.



## Hands-On Lab Module will Emphasize and Reinforce the following Learning Objectives

- How to acquire a gamma-ray spectrum emitted by uranium or plutonium and conduct an energy calibration
- List features specific to a uranium or plutonium gamma-ray spectrum that was acquired by the spectrometer.
- Recognize the difference between scintillator and semiconductor spectrometers.
- Use of an HPGe, high-resolution gamma-ray spectrometer to perform energy calibration, and to demonstrate the relationship between resolution and dead-time.
- Gamma-ray attenuation in various materials.
- Gamma-ray spectrometry counting statistics (optional)